Performance of Polymer-encased Concrete Walls Subjected to Blast Loads

Authors:

James S. Davidson, Associate Professor, Department of Civil and Environmental Engineering, The University of Alabama at Birmingham, Birmingham, Alabama 35294. *jdavidso@uab.edu*

Jeff W. Fisher, Senior Engineer, Applied Research Associates, Inc., P.O. Box 40128, Tyndall AFB, FL 32403. *Jeff.Fisher@tyndall.af.mil*

Robert J. Dinan, Senior Research Engineer, Air Force Research Laboratory, 139 Barnes Drive, Suite 2, Tyndall AFB, FL 32403. *Robert.Dinan@tyndall.af.mil*

INTRODUCTION AND BACKGROUND

Military and diplomatic facilities are targets of terrorist bomb attacks. Unfortunately, terrorists also commonly target populated public facilities such as residential buildings, office buildings, and restaurants. Most casualties and injuries sustained during external explosions are not caused by the pressure, heat, or container fragments resulting from a bomb detonation. Rather, most injuries are blunt trauma and penetration injuries caused by the disintegration and fragmentation of walls, the shattering of windows, and by non-secured objects that are propelled at high velocities by the blast. Ensuring that the exterior walls of a structure are able to withstand a blast without producing deadly fragments is a critical part of minimizing injuries to building occupants. Most common building wall structures are not designed to withstand blast loading. The resistance of a wall to blast loads can be enhanced by increasing the mass and ductility of the wall with additional concrete and steel reinforcement, which can be time consuming and expensive. For these reasons among others, a need has arisen for cost effective methods of designing and constructing walls that can resist significant levels of blast pressure.

Over the past decade, the Force Protection Branch of the Air Force Research Laboratory (AFRL) has conducted research towards developing lightweight, expedient methods of strengthening structures against blast loading. As part of the Materials and Manufacturing Directorate of AFRL, our technology development activities emphasize the use of advanced materials for force protection applications. Recent successes include the pioneering use of spray-on elastomeric polymers and sheet polymers to retrofit-strengthen masonry walls for blast loading [1, 2]. The polymer retrofit program emphasized the ability of a thin backing of low strength, highly-ductile elastomers to increase the resistance of brittle concrete masonry walls to blast loading. The polymer retrofit program continues; however, AFRL recently began looking into other forms of walls that could take advantage of the ductility of polymeric materials for blast resistance. As a natural extension of the polymer retrofit program, we began investigating the advantages of permanent (stay-in-place) plastic concrete formwork for protective structures applications.

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14. ABSTRACT

This paper discusses recent testing and finite element simulation of stay-in-place polymer concrete forms. Static tests provided a definition of resistance mechanisms. Dynamic tests demonstrated improved blast resistance effectiveness over other standard concrete wall forms. The finite element simulations provide a high level of understanding of resistance mechanisms, fracture propagation, influence of support conditions, etc., over the duration of the flexural response. The knowledge gained from the testing and simulation work was used to develop a single-degree-of-freedom approach that can be used for design and analysis.

15. SUBJECT TERMS

Blast protection, structures, polyvinyl chloride, concrete, blast resistance

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The overall objective of the research described herein is therefore to investigate and describe the effectiveness mechanisms of walls comprised of permanent concrete formwork for resisting blast loads, and to develop an engineering definition of the resistance provided by polymer-encased concrete wall systems subjected to blast loading. Static flexural tests and full-scale explosive tests were conducted. Also, high-fidelity finite element simulations were used to further understand resistance mechanisms. Efforts thus far have focused on walls without internal steel reinforcement. Future efforts will involve other configurations of stay-in-place forms and resistance definitions that include internal steel reinforcement. This paper highlights static testing, dynamic testing, finite element modeling approach, engineering resistance definitions, and implementation and accuracy of single-degree-of-freedom (SDOF) models.

DESCRIPTION OF STRUCTURAL CONFIGURATIONS

Two polymer concrete form systems were considered for the initial phase of the research [3, 4]. Both systems use PVC (polyvinyl chloride) extrusions for the forms and can be designed with or without internal steel reinforcement. The primary difference between the two systems is in the number of extrusions used to create the wall configuration: one system uses separate extrusions for the exterior face, interior face and connecting webs while the forms of the other system are manufactured as a single extrusion. Figure 1 illustrates the system chosen for the initial stage of the research.

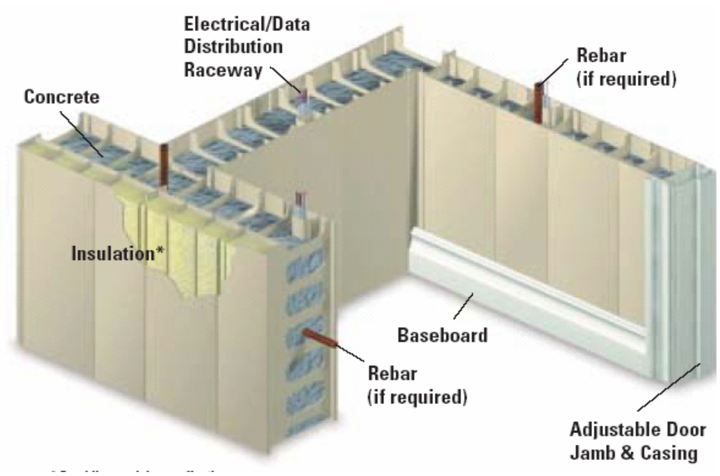

FIGURE 1
POLYMER FORMWORK WALL SYSTEM [3]

The system is comprised of an extruded PVC shell in which the external walls are connected by a web with oval cutouts that provide continuity between vertical segments. Four thicknesses were considered: (1) 4-inch, (2) 6-inch, (3) 8-inch, and (4) 8-inch with

2-inch thick insulating foam. Construction simply involves setting the PVC forms, reinforcement (if designed with reinforcement), and support anchors in place, and then filling the forms from the top with concrete. The concrete is allowed to flow between vertical panels through the oval cutouts, thus providing lateral continuity between panels.

The mechanical characteristics of the PVC materials used in the forms were defined using ASTM D-638 testing procedures. However, as with most polymers, the stress-strain characteristics vary significantly with rate of strain [5]. Therefore, since the response of the system to blast load may result in high rates of strain, specimens were tested at varying rates to quantify strain rate effects on mechanical behavior. Figure 2 illustrates the findings of the tensile tests at stroke rates of 2 in./sec and 200 in./sec. Additional mechanical information on the PVC used in the systems can be found in other sources [6, 7, 8]. In general, the PVC used in these systems has a maximum engineering tensile strength of approximately 7,200 psi, a clear yield point at approximately 7.5% elongation, and an ultimate elongation of approximately 30%. Toughness decays as the rate of strain increases. Furthermore, elongation at maximum strength and initial modulus indicates that the PVC softens at higher strain rates.

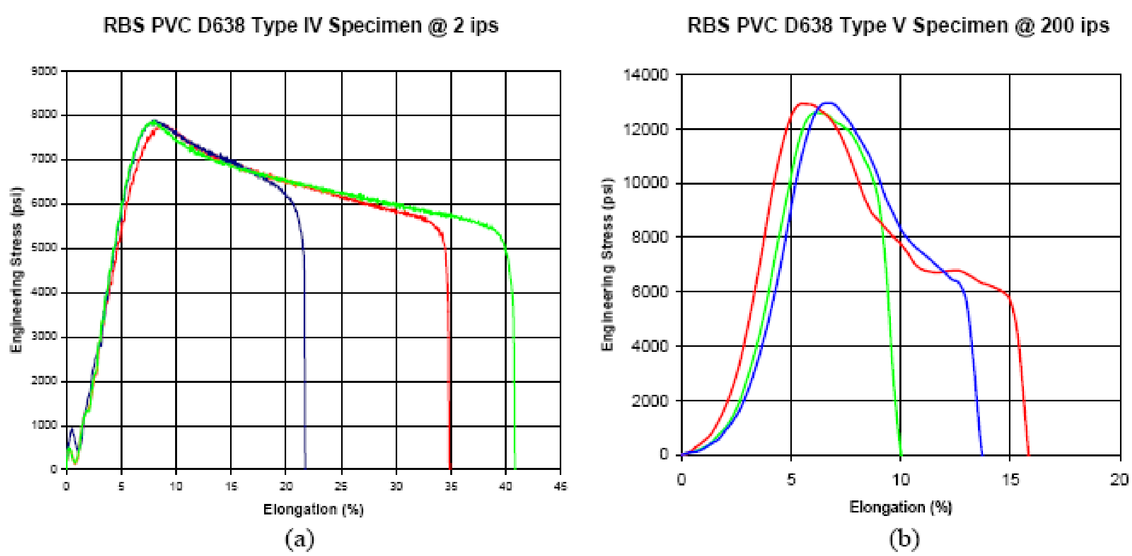

FIGURE 2
PVC STRESS-STRAIN PERFORMANCE AT 2 IN./SEC AND 200 IN./SEC

STATIC FLEXURAL TESTS

Quarter-point bending tests (similar to ASTM E72) have been conducted on PVC form wall panels by others [8, 9]. These tests illustrated significant composite action and ductility provided by the PVC components of the system. However, the tests were not conducted to failure, whereas a definition of blast energy absorbing ability through ultimate strength is important for blast resistant design. Therefore, to provide additional understanding of resistance mechanisms through ultimate rotation capacity, additional tests were conducted by AFRL with particular focus on (1) slippage between the PVC and concrete, (2) the role of the PVC webs with cutouts, and (3) effects of high loading rates on composite action.

AFRL designed a “wrench test” for a standard MTS machine which allowed the breaking of samples in flexure using a one second loading cycle (Figure 3). The tests provided understanding of the cracking and failure mechanisms as the response transitions from uncracked to cracked to maximum strength to rupture. The testing apparatus was designed to be rigid in order to minimize vibration in recorded load data at high loading rates. A sample of the recorded test data for each stroke rate is shown in Figure 4 for the 8-inch form.

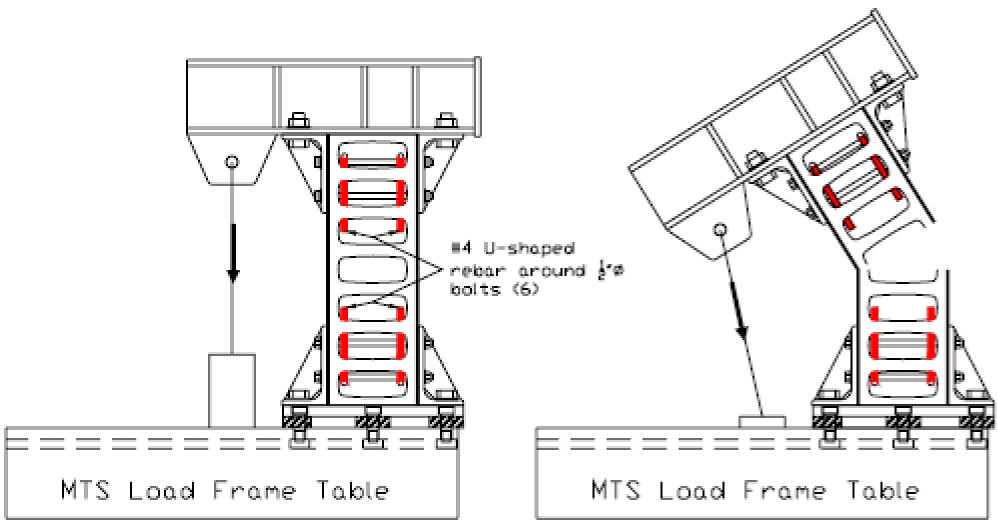

FIGURE 3
ILLUSTRATION OF THE WRENCH TEST

The first peak coincides with the initial concrete crack and is followed by an immediate drop in load as the crack separates and tension force is transferred to the polymer. At the two higher stroke rates small load oscillations (vibration of the test apparatus) occur as the stress in the PVC increases. A second peak associated with a second crack in the concrete occurs for the two slower rates. The load temporarily drops as the second crack separates and the PVC reloads. At the 0.003 stroke rate, the PVC had already reached maximum strength before occurrence of the second concrete crack, so the subsequent reloading of the PVC did not exceed the second data peak. For the 0.167 stroke rate, the PVC reached its maximum strength after the second concrete crack. Slippage at the PVC - concrete interface was evident, and occurred immediately after concrete cracking. The PVC tensile failures were significantly different from the slowest to highest stroke rates. PVC at the higher stroke rates exhibited brittle fracturing while failure at slower rates exhibited discoloring and stretching prior to rupture. Photographs of these contrasting failure types are illustrated in Figure 5.

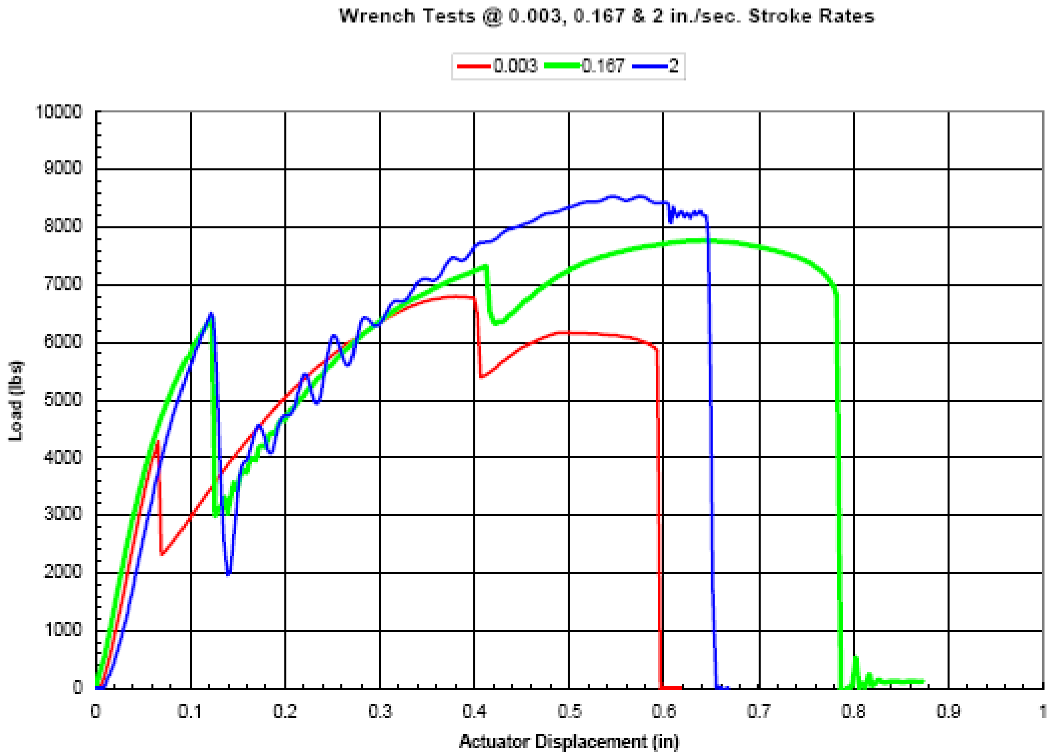

FIGURE 4
WRENCH TEST DATA FOR THE 8-INCH GEOMETRY

(a) Failure @ 0.003 in/sec Stroke Rate

(b) Failure @ 2 in./sec Stroke Rate

FIGURE 5
WRENCH TEST PVC FAILURES

DYNAMIC TEST RESULTS

Thus far, six PVC form walls of various thicknesses have been tested in three separate detonations. The experiments are summarized in Table 1. The purpose of the sand/gravel-filled wall experiment (Wall #6) was to investigate the amount of the deflection resistance that was due to mass effect versus the resistance provided by the uncracked concrete and subsequent composite PVC-cracked concrete resistance. However, the sand/gravel mixture was 7.2% lighter than the concrete used in Wall #1, which precludes a direct comparison.

Wall #	Description	Results and Observations
1	8-inch PVC form, 12 ft vertical span, dowelled into concrete at the base and a pin restraint at the top.	No external damage or residual deflection, peak inward deflection of 2.8 inch.
2	8-inch PVC form with 2-inch insulation, 12 ft vertical span, dowelled into concrete at the base and a pin restraint at the top	No external damage or residual deflection, peak inward deflection of 4.7 inch.
3	4-inch PVC form, 9 ft vertical span, dowelled into concrete at the base and a pin restraint at the top.	Tension failure in PVC at mid-height /11.2 inch defection, wall collapsed.
4	6-inch PVC form, 9 ft vertical span, dowelled into concrete at the base and a pin restraint at the top.	Tension failure in PVC at mid-height, 6.4 inch defection, wall did not collapse, peak inward deflection of 9.3 inch.
5	4-inch PVC form, 9 ft vertical span, dowelled into concrete at bottom and top as retrofit behind unreinforced 8 inch CMU wall.	No external damage or residual deflection, peak inward deflection of 5.1 inch.
6	8-inch PVC form filled with sand/gravel mix only, 12 ft vertical span, pin restraint at bottom and top.	No external damage or residual deflection, peak inward deflection of 6.1 inch.

TABLE 1
DYNAMIC TEST SUMMARY

FINITE ELEMENT ANALYSES

Use of advanced computer modeling techniques is essential to understanding the behavior of structures subjected to blast. The short duration of loading and response plus the destructive result of the testing eliminates the opportunity for thorough understanding of structural response being gained exclusively from explosive tests. Furthermore, full scale explosive tests are too expensive to be used to examine every important parameter. The objectives of the modeling aspects of this effort were to (1) provide insight into the distribution of strain over the response time interval and thus to better understand failure mechanisms, (2) to complement data taken during a minimum number of explosive tests with parametric analyses involving a wide range of variables, and (3) to thoroughly investigate and adopt modeling techniques that could be used to explore the feasibility of other permanent formwork concepts. The modeling effort is on-going, but the following discussion summarizes simulation methodology and important knowledge gained thus far.

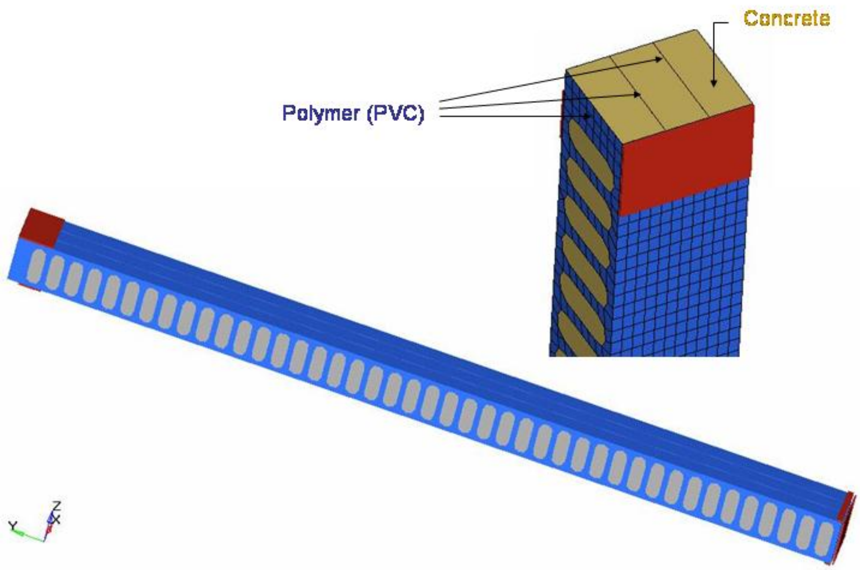

FIGURE 6
FINITE ELEMENT MODEL

An explicit-formulation finite element solver, LS-DYNA-3D (10, 11), was used. DYNA-3D is known for its capabilities and efficiency in solving highly nonlinear dynamic problems such as penetration mechanics, response of structures subjected to blast, and motor vehicle crash. It has a wide range of material property options developed to simulate materials in high strain rate environments as well as the ability to simulate contact interfaces and separation of discrete components. One-way flexure models were constructed. A refined mesh (approximately 20,000 elements) was required to simulate the fracture patterns observed in the tests. Model development challenges included simulating the interaction with supports, incorporating gravity preload effects, modeling the concrete/PVC interfaces, choosing material models capable of simulating the behavior of the PVC subjected to high shear and tension under high strain rates, and simulating PVC/concrete interface separation. The one-way flexure model illustrated in Figure 6 uses a brittle constitutive model for the concrete (MAT_BRITTLE_DAMAGE), and uses tied-node features of DYNA-3D to simulate the discrete component interaction between the concrete and the PVC. The interaction of the wall structure with the supports was simulated with rigid contact definitions. The PVC form components were modeled with shell elements. A study of the applicability and stability of LS-DYNA material models developed for rubber and plastic behaviors resulted in the MAT_PIECEWISE_LINEAR_PLASTICITY chosen to represent the polymer used in the explosive tests. The polymer shell elements were tied to the concrete elements using contact interface capabilities and tied-node failure rules so that the effect of bond strength between the concrete and PVC on the system behavior could be studied. An excellent agreement between the DYNA-3D models and the accelerometer and deflection results from the dynamic tests was achieved and behavioral observations were noted. Figure 7 illustrates a deflection comparison to Wall 1 dynamic test.

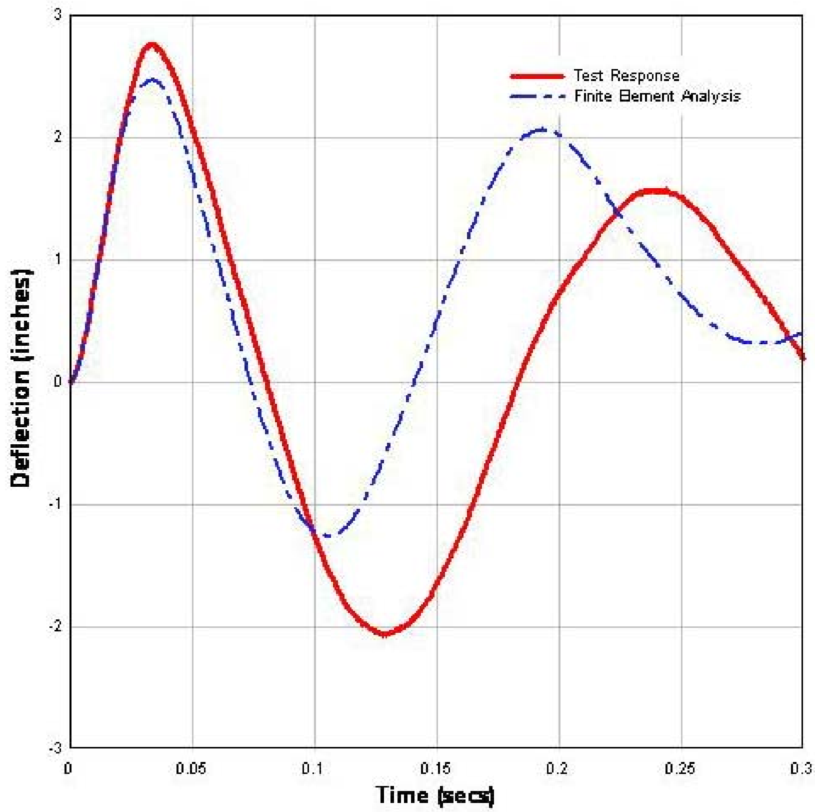

FIGURE 7
COMPARISON BETWEEN FINITE ELEMENT MODEL AND TEST DATA

RESISTANCE DEFINITION AND SDOF MODEL

Once the general resistance mechanisms of the structure are understood, the knowledge must be translated into a form useful for engineering analysis and design. For protective structures applications, this is typically accomplished through easy-to-use single-degree-freedom models. The real behavior of the composite PVC-concrete flexural structure is enormously complicated. However, the peak deflection of the system can be predicted to adequate accuracy for engineering analysis and design through simplifying assumptions that capture the predominant resistance mechanisms. This peak deflection prediction can then be translated into the forces, stresses, strains, etc., required for design.

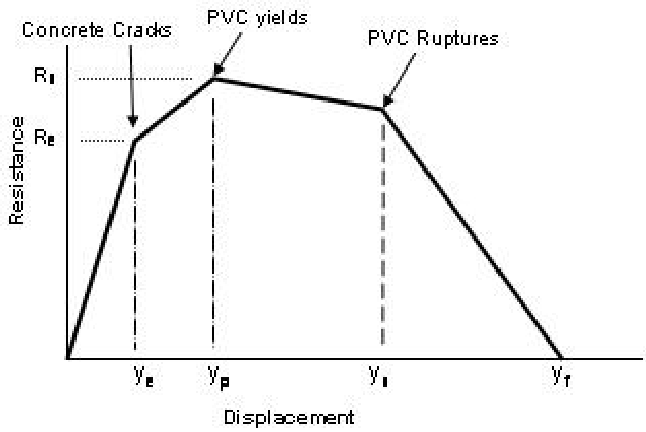

FIGURE 8
RESISTANCE FUNCTION ASSUMED FOR THE PVC FORMWORK CONCRETE WALL

SDOF analyses require three basic definitions: (1) loading function, (2) mass function, and (3) resistance function [12]. For the blast loaded wall application, the system is idealized as a one-way flexural member (essentially a beam of unit width). The loading function simulates the dynamic pressure resulting from blast, and, in general, is comprised of an instantaneous peak followed by a nonlinear decay. A negative loading phase may also occur, but is typically ignored in SDOF analyses. To further simplify the analysis, a triangular load pulse is used that matches the peak pressure and impulse, but has a shorter duration than the true duration of the load. The mass function is not the full mass of the wall, but rather must reflect the mass contributing to the kinetic energy of the system after the concrete has cracked. The resistance function represents the relationship between static uniform pressure and mid-span deflection. For the polymer-encased concrete wall system, the derivation of this function involves a wide range of parameters such as the concrete compressive and tensile strengths, mechanical properties of the PVC, cross section geometry, and length. Furthermore, the failure mode of the system subjected to static loading may differ substantially from that of the system subjected to blast loading, plus the failure mode under dynamic loading may depend upon the peak pressure and impulse that is applied. An illustration of the resistance function for a PVC encased concrete wall is shown in Figure 8. A preliminary comparison is shown in Figure 9, where a consistent 60-80% difference is achieved between the high fidelity finite element approach and the SDOF approach. Although current efforts are on-going to improve the resistance definition which will result in better correlation between the SDOF and testing/FEM approaches, the difference using the current definition is consistent and would result in conservative designs.

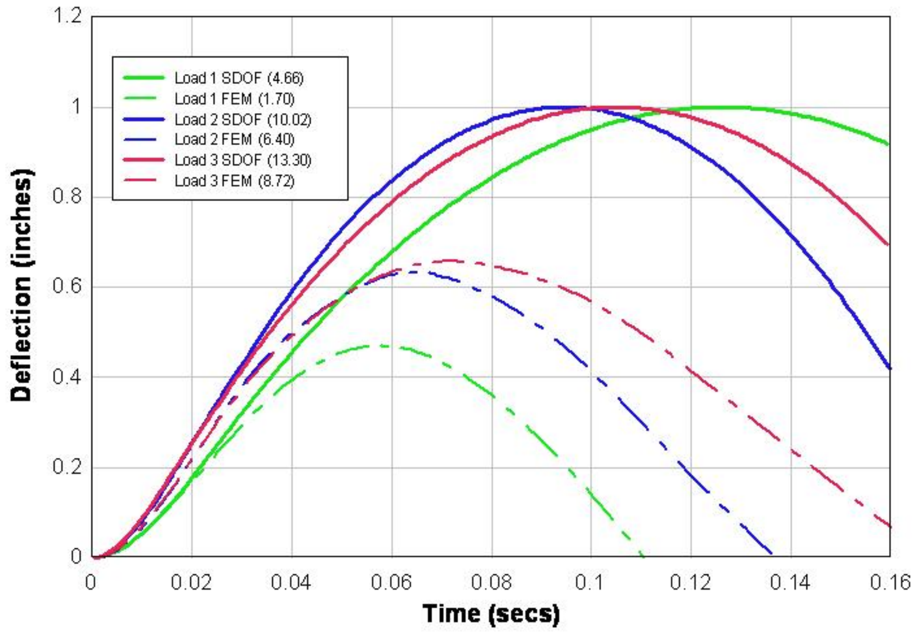

FIGURE 9
COMPARISON BETWEEN SDOF AND FINITE ELEMENT

CONCLUSIONS AND CONTINUATION

Stay-in-place PVC forms provide significant blast protection compared to concrete walls without the polymer constituents. The composite behavior between the concrete and PVC provides several advantages. The material characteristics of the PVC that contribute to improved effectiveness include: (1) significant increase in strength as strain rate increases and (2) the elongation capacity of the PVC facilitates significant energy absorption as the deflects. These two attributes combine to allow considerable wall deflection. The PVC encasement also offers the advantage of capturing concrete spalling and wall fragments as the wall deflects and fails. Through full scale blast testing and high fidelity finite element simulations, the single-degree-of-freedom was demonstrated to be a viable method to predict wall response for walls constructed with stay-in-place PVC forms.

AFRL plans to continue the development and improvements of the resistance definitions and SDOF models. The next research phase will extend the knowledge learned in this phase to rebar reinforced walls with and without openings for doors and windows. Strain compatibility between the rebar and PVC during blast response is anticipated as an important element for the next research phase. Future full-scale experiments will consider physical and video methods to capture deflection at multiple wall heights to validate deflection shape assumptions.

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